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Abstract
The paper describes a framework of an interactive advising system for machinery **condition monitoring.** Such expert system has been designed with a modified strategy to be a viable alternative to regular periodic inspection. This strategy has been structured to provide alarms of any departure from normal machinery conditions determined from measurements collected in operating modes. Such modes include passive loading and on-load for new machinery of both short and long life as well as for reconditioned return-to-action machinery. Moreover, the **monitoring** strategy is equipped with knowledge and rules which are mainly based on Canadian Government specification CAD/MS /NVSH 107. With this strategy, detection of developing faults that would otherwise have gone undetected until perhaps a breakdown occurred should be more possible. Furthermore, a scheduler has been embedded in to keep track of user-specified **monitoring** frequency and to give a warning of any drop-out on **vibration** measurements recordings or of any inspection-due-machine left out of the **monitoring** process. The system is laid out with the aim of building up machinery **condition** history to help management evaluate machinery performance. (24 refs).

Descriptors

Expert System for Vibration Condition Monitoring of Rotating Machinery

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ABSTRACT

As technology greatly advances, machinery are getting so sophisticated and expensive that the need for fault detecting inspection system, through which maintenance critical decision can be made, keeps on rising.

This paper describes a framework of an interactive advising system for machinery condition monitoring. Such expert system has been designed with a modified strategy to be a viable alternative to regular periodic inspection. This strategy has been structured to provide alarms of any departure from normal machinery conditions determined from measurements collected in operating modes. Such modes include passive loading and on-load for new machinery of both short and long life as well as for reconditioned return - to - action machinery. Moreover, the monitoring strategy is equipped with knowledge and rules which are mainly based on Canadian Government specification CAD/MS/NVSH 107.

With this strategy, detection of developing faults that would otherwise have gone undetected until perhaps a breakdown occurred should be more possible. Furthermore, a scheduler has been embedded in to keep track of user-specified monitoring frequency and to give a warning of any drop-out on vibration measurements recordings or of any inspection-due-machine left out of the monitoring process. The system is laid out with the aim of building up machinery condition history to help management evaluate machinery performance.

This expert system which can be applied almost to any rotating machinery provided its mechanical structure is known, should provide valuable information regarding the mechanical health of machinery and can result in considerable gains in machine up-time as well as substantial savings in spare parts and in repair time costs.

KEYWORDS: Vibration condition monitoring, Expert system, and Predictive maintenance.

1. INTRODUCTION

The right choice of monitoring, ensures optimum maintainability programme [1]. The type of monitoring adopted here is condition monitoring. This approach applies to a broad system of specific measurement of significant parameters of a machine in operation whereby its condition can be assessed. Its particular significance is that any deterioration of machine condition can be detected at a early stage without having the machine taken out of service or stripped down for inspection. Thus, impending failure can be diagnosed and located at the onset when remedial action is relatively inexpensive and shut down time for this work can be planned in advance.

Significant monitoring parameters relative to all types of machines can be temperature, position, process variables, sound and vibration. Vibration monitoring, adopted in this research work, is the most significant parameter [2-4], on the basis that characteristic vibrations are associated with particular phenomena in rotating machines and any change in the vibration signature signifies a change in condition.

The subject of machinery condition monitoring has attracted few scientists (5-15). Neale (15), for instance, has cited the benefits of condition monitoring, while Philip et al. (16) has described a concept of a continuous monitoring system. Recently, however, a new approach to condition monitoring has been devised by Gottlich (17). Such approach was based on a new theory of calculating the actual efficiency of the machine. Walter et al. (18), on the other hand, demonstrated that an understanding of pumps vibration modes is required for effective monitoring of their operational health.

Experience Suggests that the probability of a correct and speedy detection greatly increases when a record of past vibrational behavior is built up in a systematic manner. However, with the steady increase in complexity of equipment in factories where stringency of operating conditions and where important expensive machines are not duplicated or where unscheduled production stops can result in large losses, it becomes obligatory, however, harder to detect departure from normal operation of equipment. To solve this dilemma more emphasis is placed on artificial intelligence.

Artificial Intelligence techniques are playing an increasingly prominent role in designing computer-based tools such a expert systems. Expert systems is a class of programs that has been successfully devised to bring large quantities of information to bear encountered problems whether of medical, electrical or mechanical nature. These systems are considered "intelligent" as they simulate the reasoning of human experts by using knowledge to infer what is unknown based upon what is known.

Lately, scientists implemented artificial in industry. For instance, Jeffery (19) designed an artificial intelligence program to advise engineers regarding failures of fractured metallic parts, while weld faults were identified by an expert system using radiographic technique (20). Also, Haran et al. (21) used artificial intelligence to inspect railroad wheels using acoustic signature.

Alternatively, Smiley (22) discussed implementing expert system for monitoring for the factory of the future. In specific, however, Peter et al. (23) found out that expert system technology can be effectively applied to real world of maintenance problems. Furthermore, Hill et al. (24) has pointed out the considerable advantages that can arise from incorporating an expert system within the framework of condition monitoring systems. Unfortunately, making use of computer-based tools to help in the narrow domain of maintenance, particularly, in machinery vibration monitoring, up to our knowledge, has not yet attracted many scientists.

This paper describes an expert system which has been developed at the American University in Cairo (AUC-CEP) to perform off-line vibration condition monitoring of rotating machinery. Such expert system is equipped with a modified monitoring procedures and strategy, to arrest problems before they cause acute failure along the different stages of machinery operation life cycle.

2. MONITORING STRATEGY

Vibration Condition monitoring is applied here on the basis of manual periodic logging of measurements at pre-determined time intervals into database. The appropriate frequency will vary from location to location, depending on the vibrational history of the machines. In the measurements process, machinery overall vibration readings are collected consistently at or as near as possible to the check points in operating modes. Such modes include passive loading and on-load for new as well as for reconditioned returned-to-action machinery. Upon exceeding a preset threshold vibration located in the rule/knowledge base, the out of limit readings are displayed to the operators with a blinking alarm. This is to ensure that overall vibration levels are kept within prescribed limits and any detected significant departure from normal behavior is analyzed.

In the analysis, machinery spectra are recorded consistently under similar conditions using the same check-points locations in three directions, namely, horizontal, vertical and axial. Such spectra are then split the into components in terms of peaks amplitude with their corresponding speed frequencies. These components are examined against the mean value and variance calculated per one direction at a time in each operating mode. The probability of locating a fault greatly increases when a direction holds the highest mean value and variance along with the highest vibration amplitude at a certain check-point in either operating mode. This analysis assists primarily in detecting developing faults that would otherwise have gone undetected until perhaps a breakdown occurred. Maximum use of the information content in the vibrational signal can therefore be made for diagnostic purposes, which is beyond the scope of this paper, where knowledge of this nature can provide conclusive evidence of a specific fault.

The detailed strategy may vary in implementation from a location to location, but, when laying out monitoring strategy distinction should be made between new and reconditioned returned-to-action machinery in any operating mode. Such distinction should provide a sufficient data for efficient record keeping of machinery history.

In the case of on-load measurements, scheme includes two types of data. The first is the response of the machine over the complete speed range and the second is the response to loading which is necessary to identify any load-dependent variations. The passive loading measurements, on the other hand, are concerned with machinery running either by itself with no load connected on line or after load has been released. The purpose of on-load or passive loading measurements is to enable the actual in-service behavior of machinery to be assessed, and to ensure that it is included in its history recording for later analysis. A recommended strategy is to record all passive loadings, when possible provided that the number of operation hours on the machine is recorded since the last monitoring.

Upon return-to-action, machinery's previous history prior to the overhauls, is no longer a reliable baseline against which changes can be assessed. Therefore, it is essential to obtain sets of repeatable data evaluating and defining the machine performance. However, the nature of the measurements may vary from one location to another, depending on the type of machines as well as, the nature and frequency of the vibrational problems associated with them.

Once a deviation of the normal performance has been detected, the operator may have to respond immediately if commercial vibration limits are exceeded by either reducing load, running the machine down or other means, to ensure machine safety. This has to be followed up by initiating a detailed investigation of the encountered phenomenon. Such investigation can lead to a form of correction including changing operational procedures, maintenance procedures & actions and/or design modification.

3. STRUCTURE OF THE PROGRAM

The structure of this advising system is based on three components, namely, 1) database, 2) knowledge/rule base and 3) inference engine. These components, as shown in figure 1, are linked together to produce a system that advises and informs about encountered problems in a manner similar to that of one or more human experts.

3.1 Data Acquisition Subsystem

The data acquisition subsystem incorporated here is in fact the system database which is designed to accept, manage and manipulate conditioned and processed data from the keyboard. It consists of five modules, namely, system management database, machine database, route database, recording database and security database as shown in figure 2. The system database is accessed directly by the system management database which is termed Master database.

3.1.1 Master database

Master database is a register provided to serve several purposes. These purposes include 1) interface with operator through the keyboard, 2) control system hardware configuration, 3) direct access to database and expert system, 4) overall system control of file handling through password and identification number and thus 5) protect data input against accidents, operational errors and tamperings at any time.

Upon starting creating the system database through the initialization process, master database uses five key words with their addresses. These key words are machine code, bearing code, route code, permanent code and temporary code. The system database is so created that it is composed of current, backup

and log database files as shown in figure 1. The current database, through which data entry or updating is made, is acting as a user interface with the system; while the backup database is made to be a substitute to the current database through security keeping procedure set by the user. Upon completing the backing up process, the log database records the respective date, the changes in the data in terms of machine specification, bearing specification, route specification and the user's password with identification code number.

The system database has been built in a way to protect the data recorded against intended or unintended interruption such as sudden power breakdown, operational errors or tampering to the system. It allows only one sub-database to be invalid, keeping either the current database file or the log database file. In case of a sudden power failure during data updating or while transferring data from the current database to the backup database, the current database becomes invalid. To reconstruct, the log database should be merged with the backup database. Alternatively, if such failure occurred upon completing the backing-up and while initiating the process of updating the log database file, the latter becomes invalid. Therefore, it has to be recreated.

3.1.2 Machine Module

In machine database, the machine was broken down into components suspended through bearings termed "checking points". This database is divided into two domains, namely, machine and points. In the machine domain, machine specification, name, code, location and number of points are provided by the user. Upon entering such information, the user is transferred to the points domain. In such domain, point specifications in terms of point type, left and right components, rotational frequency, direction of measurement and limit reading are provided by the user with the objective of using such information for later measurements collection on a preset route.

3.1.3 Route Module

Route database is a register designed to follow the machines' vibration monitoring frequency. Such route load a collection of machines in a certain order to record new vibration measurements at their respective order and points and according to the frequency set by the user with the objective of keeping track of the machine monitoring frequency. This database is capable of warning the user of any drop out in data entry of certain machine or of any machine left out of the monitoring process.

3.1.4 Recording Module

Recording database is designed to keep track of the history of machines performance. In such database measurements are allowed to be recorded in two separate records, permanent and temporary. In permanent records, the program is designed to record only the acceptable machines vibration condition. Such machines are scheduled for monitoring on regular route with certain frequency for later analysis. In such analysis, the program give out warning on the screen if the measurement reading of certain machine is either above the allowable vibration level or if inspection time is overdue.

Temporary records are for monitoring-due machines. In the monitoring only one set of readings is allowed to be taken for each point according to the specific monitoring frequency set by the user through the regular route database. Upon scanning of the readings of certain machine if the program detect an out of vibration limit reading, a warning is issued and the machine database gets loaded into a temporary route for more frequent measurements. In other words, if a machine is set to be monitored monthly in the permanent records and its vibration level reached its upper threshold limit, such machine will be transferred upon the consent of the operator to another temporary records for more frequent vibration measurement i.e. weekly instead of monthly. Once that machine has been stabilized, only the last reading will be recorded in the permanent records according to the machine monitoring frequency established in the permanent route.

3.1.5 Security Module

Security database is designed to track down tamperings through recording the entered password, identification code and any changes might have been made. In addition, this procedure allows the permitted user to retrieve original old valid data and thus it was made to protect the original data recorded in the system.

3.2 Expert system

The primary function of the expert system part is to convert monitored data into meaningful information. There are a number of reasons why expert systems are a very effective part of modern condition monitoring systems. Such reasons include: 1) Detection repeatability, 2) incorporating the knowledge of more than one expert, 3) the availability of the expert system at any time, 4) the availability of the expert system at different locations at the same time, and 5) the ease of updating or adding knowledge to the knowledge base due to the fact that the knowledge base is not part of the inference engine. The expert system is mainly composed of two parts, namely, rule/knowledge base and inference engine.

3.2.1 Rule/Knowledge Base

The performance of an expert system is critically dependent upon the knowledge that is embedded within it. Rules and knowledge must be established to cover the anticipated behavior of a machine in a given set of circumstances. The major sources of input to the knowledge base can be on the form of 1) operational experience, 2) maintenance or operation manuals, 3) fault history with measurement records, 4) manufacturer recommendations and 5) cause and effect relationships.

The information encapsulated here in the knowledge base is classified under on-load and passive loading limits. As to on-load limits, mean and variance method is adopted for both filtered and unfiltered measurements. In such a method, analysis is done first per direction and then per check point.

The passive loading limits are in terms of the overall velocity RMS for different type of machines and at different life. The machines are classified under two categories 1) new and worn ones. The new machines class can be classified to short life (100-1000 hrs) and long life ones (1000-10000 hrs). Both are controlled by given values of the acceptable limits of bearing vibration.

The worn machines class, however, is classified into machines calling for recondition and reconditioned machines. Both should be monitored at full speed and power. In the former type of machines, service is called for upon reaching certain vibration limit, while in the latter, call for repair upon exceeding specif[illegible] tion limit.

The information related to passive loading limits is an extract from the Canadian Government specification CAD/MS/NVSH 107 for bearing measurements in the range of 10 to 10000 Hz. It gives values of acceptable limits of bearing vibration for a number of different machine types. Such machines are gas and steam turbines, compressors, diesel generators, centrifuges oil separators, gear boxes, boilers, motor generator sets, pumps, fans, electric motors and transformers. The knowledge base can always be updated. The ease with which the knowledge base can be altered plays a vital part in this refinement process and also in the reasoning process.

3.2.2 Inference Engine

The inference engine provides the expert system with the ability to arrive at a decision through the reasoning method. The reasoning method adopted here in this paper is the Goal Tree-Success Tree (GTST) method. In such a method, the end points of the goal tree use operating knowledge in the form of "if-then rules" instead of success. Details about this method can be found in reference (15).

The inference engine is basically a program that uses the knowledge base to operate upon the measurements collected in the database through certain chain strategies. The two most common strategies known to perform the inference process are termed forwards and backwards chaining. In the former, the inference process starts from a new piece of data and searches through the rules to find which ones are satisfied, and hence identify if there are any abnormal behavior present. The latter strategy, however, starts from a particular deviation and then works backwards through the rules to the point where the implied conditions satisfy the information available in the database. If all conditions are satisfied then the fault is judged to exist. In this paper, the forward chaining strategy was adopted.

4. DESIGN CONSIDERATIONS

The program has been designed for use by two types of users in addition to the regional information center within the maintenance organization. Such users can be station operators whose prime responsibility is feeding data to the system although they may not be able to understand its cause, and machinery maintenance specialist who should be capable of initial detection of a problem as well as of driving more detailed information towards identifying causes of alarms and hence put down the necessary maintenance procedures. This two-level system is typical of many maintenance department structure. The system database has been provided with an on-line help and an error explanation to help users learn about the monitoring system and does the work efficiently. It is worth noting here that in the program C and Prolog languages have been.

5. CONCLUSION

An interactive expert system with a built-in data acquisition system has been designed according to a modified maintenance monitoring strategy. Such system was data validated, tested and can be used on a network type of system for two level of users, namely maintenance planner and specialist, upon passing through a security code.

The system aims at detecting any departure from normal performance of machinery and identify the direction and the check point of excessive vibration level close to which the most probable fault should be located. The program is capable of warning the user of any drop out in data entry of certain machine or of any machine left out of the monitoring process. In addition, the program gives out warning on the screen if the measurement reading of certain machine is either above the allowable vibration level or if inspection time is overdue. Furthermore, upon detecting a machine exceeding the vibration limit, a warning is issued and such machine database gets loaded into a temporary route and more frequent measurements are demanded.

To track down tamperings, the program records the entered password, identification code and also any changes might have been made every time it has been accessed. This procedure allows the permitted user to retrieve original old valid data and thus it was made to protect the original data recorded in the system.

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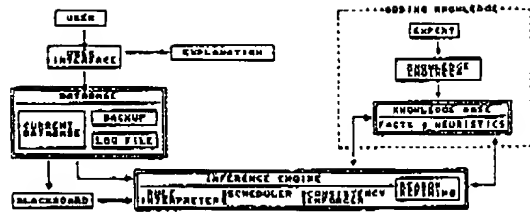

Figure 1. Architecture of the consultive monitoring system

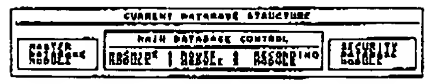

Figure 2. Structure of the system database.

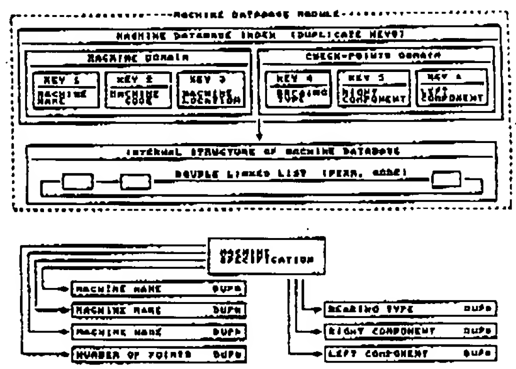

Figure 3. Functional block diagram of machine database subsystem.

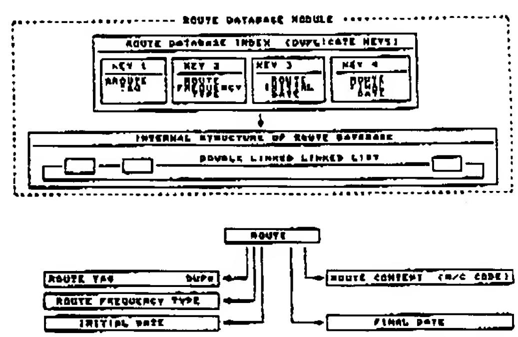

Figure 4. Functional block diagram of the route database subsystem.

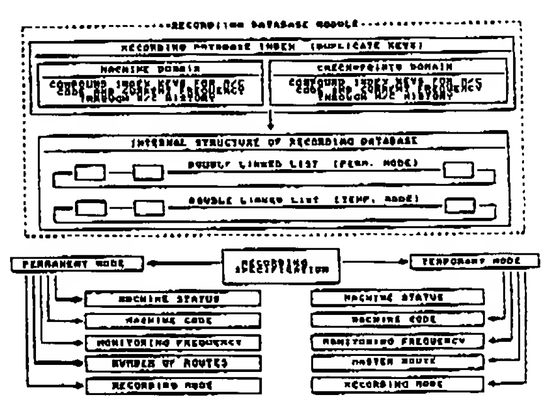

Figure 5. Schematic diagram of the recording module.